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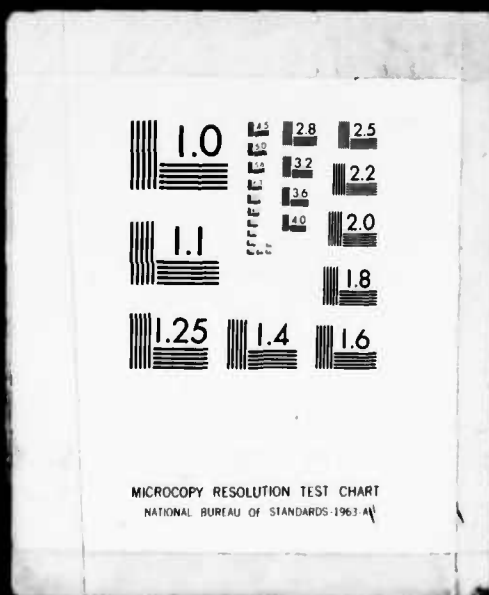
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Goals For Air Force Autonomous Spacecraft

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by
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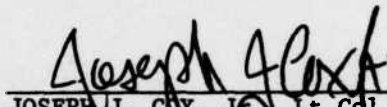
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spacecraft types and mission classes. Implementation goals, formulated in response to the policy goals, assume a functional configuration constrained by technology and resources. Functional areas/addressed are: systems (including thermal control and validation); electrical power and pyrotechnics; attitude, translation and pointing control; data processing; payload, telemetry, tracking and command; navigation; and propulsion.

As part of this effort, various levels of autonomy are developed and described. These are represented on a scale of 0 (least capable of ground independence and containing no redundant elements) to 10 (most capable of ground-independent task adaptiveness based upon unanticipated changes in the operating environment). The policy and implementation goals presented are intended to correspond to an autonomously fault-tolerant spacecraft, capable of operating in the presence of faults specified a-priori by employing spare system resources, if available, without ground intervention.

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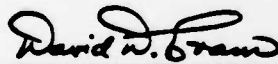
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GOALS FOR AIR FORCE
AUTONOMOUS SPACECRAFT

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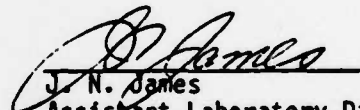
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PREFACE

This document is the initial version of the Air Force autonomous spacecraft goals document. As stated in SCOPE, Section III, these goals will be developed so as to be broadly applicable to a wide range of missions. Initially, emphasis is placed on three-axis-stabilized, geosynchronous, communication satellites. As additional information becomes available and is assimilated, subsequent revisions of this document will refine and incorporate goals dictated both by general and specific mission needs. Sources for inputs to this document are the entire U. S. Air Force Space Division community, including Aerospace Corporation, the industrial suppliers, and NASA/Air Force interagency working groups. These sources are invited to provide comments and inputs to JPL for future revisions.

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SECTION I

INTRODUCTION

During the Summer of 1980, the Space Division of the United States Air Force initiated planning for a spacecraft autonomy program intended to provide a sound technology base for significantly upgrading the autonomous capability of defense satellites by the end of the decade. The broad goal established for this program was to increase mission readiness by (listed in order of priority):

- (1) Enhancing spacecraft survivability against on-board failures.
- (2) Enhancing spacecraft survivability against hostile acts.
- (3) Reducing spacecraft dependence on ground stations, thereby enhancing the capability for system reconstitution if the ground stations were disabled.
- (4) Achieving an early satellite health and ephemeris maintenance capability by Fiscal Year 1987 (FY87), with spacecraft launched after this date capable of performing missions for unattended periods on the order of six months.

An additional goal for this program is to utilize the enhanced autonomy of spacecraft to increase the cost-effectiveness of ground operations.

The next step was to extend these broad goals into specific "working" goals which would guide the development efforts of those participating in the autonomy program; hence, the evolution of this document.

SECTION II

PURPOSE

The purpose of this document is to define goals for autonomous spacecraft which, if implemented, will instill into Air Force operational satellites launched in the late 1980's a significant autonomous maintenance and navigation capability. This capability is required to increase spacecraft survivability. Specifically, the purpose of these goals is to:

- (1) Provide a common working-level understanding, between the various participating groups, of the engineering objectives of the Air Force's autonomous spacecraft effort.
- (2) Provide a tool for assessing the autonomous capability of existing and future spacecraft.
- (3) Provide statements of autonomy-related performance needs in a format generally suitable for incorporation into procurement documentation.
- (4) Provide a common basis for assessing incremental progress in achieving autonomy objectives and for estimating the incremental cost of greater autonomous capability.

SECTION III

SCOPE

Goals presented in this document are intended to be generic, i.e., appropriate for application to the broad spectrum of Earth-orbiting satellites employed by the Air Force. These goals are intended to be applicable to the complete set of missions and orbit classes common to Air Force Programs, such as:

- (1) Surveillance missions
- (2) Meteorological mission
- (3) Communication missions
- (4) Navigation missions
- (5) Test missions

Specific mission requirements are expected to be used to select the appropriate subset of the goals which are to be applicable to that mission. These goals are formulated such that they suggest a universally desirable autonomous capability without prejudice or bias towards a particular hardware/software implementation approach.

For the purpose of this goals document, autonomy is viewed as an additional capability to that of performance capability and intrinsic reliability, as follows:

- (1) Performance capability - the capability to support payload/mission requirements when spacecraft elements are functioning properly, including the ability to endure insofar as consumable are concerned.
- (2) Intrinsic reliability - the "robustness" of a spacecraft that comes about through derated use of components, through design, parts screening, qualification testing to eliminate weakness, and the like.
- (3) Autonomous capability - that additional capability designed into a spacecraft which permits it to perform on-board task execution (with decision making) without intervention or control from the ground.

Achievement of a level of autonomous capability implied by these goals does not reduce the significance of performance goals or of intrinsic reliability goals. It is assumed that emphasis on achieving performance and intrinsic reliability will be maintained and that, additionally, a specified level of autonomous capability will simply be included which will contribute significantly to a spacecraft's overall reliability and life while providing an ability to operate without frequent ground station interaction.

SECTION IV

LEVELS OF AUTONOMY

In order to provide a means of communication on the matter of autonomous capability, the concept of "levels of autonomy" is introduced. The selected levels of autonomy serve only to provide a rough quantification of increasing capability to operate autonomously. This is represented by a scale of 0 (least capable) to 10 (most capable). The levels of autonomy are defined in the appendix and the goals presented herein are intended to correspond to, and to help define, an autonomy level of about Level 5.

It is intended that the "levels of autonomy" concept be utilized to:

- (1) Assess the autonomous capability of existing designs.
- (2) Aid in measuring progress toward the achievement of autonomy goals.

SECTION V

GOALS AND GOAL STRUCTURE

Two types of goals have been defined. They are policy goals and implementation goals. These goals must be stated in such a manner that incremental autonomous capability may be added to specific spacecraft in the near term.

A. FOCUS OF POLICY GOALS

Policy goals are focussed toward attainment of major advances in the autonomous capabilities of Air Force spacecraft. They cut across all classes of spacecraft and missions. Their attainment is required to achieve the minimum objectives of the autonomous effort. Policy goals are divided into four categories:

- (1) Ground interaction reduction
- (2) Spacecraft integrity maintenance
- (3) Autonomous features transparency
- (4) On-board resource management

B. FORMULATION OF IMPLEMENTATION GOALS

Implementation goals have been formulated in response to policy goals. They assume an implementation which is constrained by both technology and resources. Implementation goals are supportive of the technical and programmatic drivers of each mission and are defined in each of the following functional areas:

- (1) Systems (including Thermal Control and Validation)
- (2) Electrical Power and Pyrotechnics
- (3) Attitude, Translation, and Pointing Control (ATPC)
- (4) Data Processing
- (5) Payload
- (6) Telemetry, Tracking, and Command (TT&C)
- (7) Navigation
- (8) Propulsion

Within this structure, implementation goals for the systems areas, which will include design, validation, and operation considerations, flow down to and pervade the other functional areas. For this reason, implementation goals for systems are not repeated within each of the other functional areas.

SECTION VI

POLICY GOALS

The intent of the following policy goals is to characterize explicitly an autonomous spacecraft capability of Level 5 (as defined in the appendix),

A. GROUND INTERACTION REDUCTION

Autonomous spacecraft shall be capable of successfully performing their mission function for an extended period of time, without ground support, and at a specified level of conflict. Specifically:

- (1) Autonomous spacecraft shall operate without performance degradation for up to 60 days from the last initialization update.
- (2) Autonomous spacecraft shall operate for up to six months from the last initialization update. They shall do so within acceptable performance degradation limits for mission-prioritized functions as defined by each mission.
- (3) Autonomous spacecraft shall be able to recover from certain mission-unique failure modes. These failure modes shall be identified and prioritized.
- (4) Autonomous spacecraft shall be capable of restoring themselves to nominal mission performance after occurrence of a combination of non-simultaneous faults, defined a-priori, subject to the availability of spare resources. Knowledge of occurrence of such faults shall be available to the ground segment upon request.
- (5) Autonomous spacecraft shall tolerate transient faults without significant loss of mission capability. Knowledge of occurrence of such faults shall be available to the ground segment upon request.

B. SPACECRAFT INTEGRITY MAINTENANCE

The integrity of the payload data stream and usefulness of the spacecraft shall not be reduced by the addition of autonomous features. Specifically:

- (1) Autonomous features shall not decrease the performance and functional capability of the spacecraft.
- (2) Autonomous features shall not adversely affect the wearout mechanisms of consumables of the spacecraft.
- (3) Autonomous features shall not appreciably increase the period required for checkout and initialization on-orbit.

- (4) Autonomous features shall restore the spacecraft function after cessation of a hostile threat condition.

C. AUTONOMOUS-FEATURES TRANSPARENCY

Autonomous features shall be transparent to the spacecraft user. (Exceptions may include periods of fault isolation and recovery following a fault or periods during orbit maneuvering.) Specifically:

- (1) Autonomous spacecraft shall be maintained in a state such that they are capable of receiving ground commands.
- (2) The ground segment shall be able to exert executive control over autonomous management activities of the spacecraft. Faults or combinations of non-simultaneous faults shall not prevent executive control by the ground segment.

D. ON-BOARD RESOURCE MANAGEMENT

Management of on-board resources is mission- and mode-dependent. One may choose to accept a shortened useful lifetime in order to obtain maximum performance in a high level-of-conflict situation. Specifically:

- (1) Autonomous spacecraft shall be capable of adjusting space-system performance for various mission-critical modes by managing available spare resources and expendables even in the presence of faults.
- (2) Software that implements autonomous functions shall be reprogrammable from the ground.
- (3) Software shall accommodate reprogramming so that, in the event of depletion of certain resources and/or expendables, mission performance can be maximized within the limitations of the remaining resources.

SECTION VII
IMPLEMENTATION GOALS

A. SYSTEMS (INCLUDING THERMAL CONTROL AND VALIDATION)

- (1) The hardware and software architectures chosen shall not preclude the ability to add additional autonomous capabilities.
- (2) The system shall be capable of reconfiguration of spare resources at the lowest practical and reasonable level.
- (3) During autonomous operation, performance degradation may be allowable in specific cases, but only after spares are exhausted. "Graceful" degradation is preferred over precipitous change. Where possible, autonomous functions shall mitigate the effects on performance of a functional failure which occurs after spares are exhausted.
- (4) The adverse effects of faults shall not propagate beyond a subsystem interface if the faulty subsystem possesses sufficient spare resources to recover from the fault condition. Ambiguous faults within subsystem interfaces and subsystems' shared resource allocation shall be resolved by system-level mechanisms.
- (5) All fault detection and switching mechanisms shall be designed to minimize false alarms.
- (6) The spacecraft shall manage propellant usage during autonomously conducted orbit-adjust maneuvers (stationkeeping and/or relocation/ restoration) to assure mission lifetime requirements are met.
- (7) The spacecraft shall maintain system temperature control for all functional states and mission thermal environments. Furthermore, the thermal-control function shall autonomously ensure, for all mission phases, that non-catastrophic subsystem failures cannot induce thermal failures which will cause propagation of the initial failure within the satellite system.
- (8) The spacecraft shall utilize selected parametric data (electrical profiles, thermal characteristics, and state changes in the ambient environments, as a minimum) for on-board forecasting of incipient fault conditions within each of the functional areas.
- (9) The execution of any autonomous event or activity shall not be permitted to conflict with other (planned or autonomous) activities.
- (10) The spacecraft shall maintain performance and state-change records (an audit trail) to allow for reconstruction of performance, fault detection, and fault correction activities and determination of the status of resources and expendables.

- (11) The autonomous spacecraft shall maintain the spacecraft center-of-mass and center-of-pressure within limits required to support the mission.
- (12) Spacecraft autonomy shall be capable of being validated on the ground and verified on-orbit.
- (13) Validation shall determine the design margin (when applicable) of the autonomous mechanisms.
- (14) On-orbit validation and testing of autonomy features shall be accomplished without disrupting normal space-segment operations wherever possible. In those cases where some disruption is unavoidable, restoration of normal space-segment operation shall be an entirely autonomous process which is performed in a timely manner.

B. ELECTRICAL POWER AND PYROTECHNICS

- (1) Detection and isolation of load faults in power-bus loads shall be accomplished.
- (2) Power-margin management for power bus (including power sources, power-conditioning elements, and user loads) shall be maintained.
- (3) Management and control of the battery state-of-charge, discharge, and reconditioning functions shall be maintained.

C. ATTITUDE, TRANSLATION, AND POINTING CONTROL (ATPC)

- (1) The ATPC function shall be capable of autonomous attitude reference acquisition and reacquisition.
- (2) The ATPC function shall be capable of autonomous fault detection, correction, and recovery of its subsystem elements (sensors, computers, actuators).
- (3) The ATPC function shall be capable of autonomous inertial and celestial sensor calibrations to compensate for changes and/or degradation of sensor parameters. Compensation activities shall be transparent to the payload user.
- (4) Autonomous translation control shall support stationkeeping to the accuracies required to meet mission requirements.
- (5) Autonomous attitude determination shall support commanding of antennas and payload instrumentation pointing to accuracies required to support the mission requirements.

- (6) The ATPC function shall be capable of autonomous attitude-control propellant management by changing operational mode and/or parameters.
- (7) The ATPC function shall be capable of high-level command and decision-making for activities such as initiation of turns for star reacquisition, translation control, and instrument pointing.

D. DATA PROCESSING

- (1) The spacecraft data-processing function shall be provided with adequate parametric data from spacecraft sensors and subsystems so that spacecraft performance, resource status, and integrity can be determined on-board.
- (2) The spacecraft data-processing function shall be capable of performing the necessary diagnostic analysis (from available parametric data) required to assess the performance, resource status, and integrity of the spacecraft.
- (3) The spacecraft data-processing function shall be capable of implementing the necessary diagnostic analysis (from available parametric data) required to assess the performance, resource status, and integrity of the spacecraft.
- (4) The spacecraft data-processing function shall provide the necessary spacecraft control functions (commands) required for autonomous operation of the spacecraft-control and monitoring function.
- (5) The spacecraft data-processing function shall be capable of storing a) pertinent parametric data, b) diagnostic-analysis results, c) data reflecting control actions taken, and d) response data to autonomous control actions necessary to allow ground reconstruction of spacecraft state for time intervals up to six months. These data shall be available for ground assessment upon request.

E. PAYLOAD

- (1) Failure modes within the payload function shall not propagate into other spacecraft functions.
- (2) Redundant functional command and control paths through the payload function shall not be inhibited by autonomous features.

F. TELEMETRY, TRACKING, AND COMMAND (TT&C)

- (1) The TT&C function will cause a message to be transmitted to the

ground at the first opportunity following an autonomous management activity.

- (2) The TT&C function shall be prepared to receive ground commands at any time while in the autonomous state.
- (3) The TT&C function shall be capable of transmitting, at the discretion of ground control, normal telemetry and ranging while in the autonomous state.

G. NAVIGATION

- (1) The spacecraft shall maintain the orbit within specified limits for 60 days from the last required initialization.
- (2) If ground supervisory contact is not reestablished after 60 days of autonomous navigation, the spacecraft will continue to operate within acceptable limits even if the navigation function performance is degraded. Performance degradation will be measured by the effects of degraded orbit control on payload performance.
- (3) Spacecraft orbit state or orbit-derived data shall be available to other on-board subsystems and/or user ground facilities as required. Potential examples: Sun-Earth-vehicle angle to attitude control, Sun-occultation predictions to attitude control and power, lunar-occultation prediction to attitude control, and station-acquisition data to ground- and antenna-pointing vector.
- (4) The spacecraft shall have the capability to accept initialization-state data from the ground or an external source such as the Global Positioning System. It shall have a limited-state reinitialization capability for some range of orbit parameters perturbed about the nominal operating orbit.
- (5) The navigation function shall be capable of adjusting performance limits based upon the availability of limited resources.
- (6) The navigation function shall be capable of executing an evasive maneuver, if required.
- (7) The navigation function shall be capable of reestablishing the normal orbit, within acceptable limits, following an evasive maneuver, if required.

H. PROPULSION

- (1) The propulsion function shall detect and isolate autonomously any failed or degraded thrusters and reconfigure the thruster complement to support mission functions.
- (2) The propulsion function shall detect and isolate autonomously any leaking propellant-supply components, including tanks.
- (3) The propulsion function shall manage autonomously any limited-life components (e.g., monopropellant thrusters) to meet life-time requirements.
- (4) The propulsion function shall be capable of estimating a-priori any impulse delivered to support navigation maneuvers and attitude-control functioning.

APPENDIX

LEVELS OF AUTONOMY

In performance of a space mission, four major policy goal categories have been identified. These are:

- (1) Ground interaction reduction.
- (2) Spacecraft integrity maintenance.
- (3) Autonomous features transparency.
- (4) On-board resource management.

The extent to which these goals have been accomplished to date has been through a mix of functions resident in either the space segment or the ground segment. Furthermore, the ground segment, as an integral part of the total system, has been responsible for accomplishing maintenance, navigation mission control, and payload data processing. Thus, only minimal spacecraft autonomy has been needed.

The levels of autonomy described in this appendix are used to define a step-wise increase in spacecraft autonomous capability. By proceeding through the levels, autonomous capability is increased in the space segment and dependency on the ground segment is reduced.

The levels of autonomy are described as follows:

Level 0. A design without redundant elements which meets all mission needs by operating without the on-board control of state parameters (such as rates and position). May respond to a prespecified vocabulary of external commands, but cannot store command sequences for future time-or event-dependent execution or validate external commands. (An open-loop, on-board system controlled from the ground.)

Level 1. Includes Level 0 but uses on-board devices to sense and control state parameters (such as rates and positions) in order to meet performance needs. Is capable of storing and executing a prespecified command sequence based on mission-critical time tags. Will respond to prespecified external commands, but cannot validate external commands. Functionally redundant modes may be available for a degraded-performance mission.

Level 2. Include Level 1 plus the use of block redundancy. Ground-controlled switching of spare resources is required. Uses cross-strapping techniques to minimize effect of critical command link (uplink) failure modes. Significant ground-operator interaction is required to restore operations after most faults if spare spacecraft resources are available.

Requires operator interaction for fault recovery. Is capable of storing and executing mission-critical events which are sensed on-board and may be independent of time.

Level 3. Includes Level 2 and is capable of sensing prespecified mission-critical fault conditions and performing predefined self-preserving (entering a safe-hold state) switching actions. Is capable of storing contingency or redundant software programs and being restored to normal performance (maintaining the command link with a single link fault) in the event of a failure. Timers may be used to protect resources. Requires ground operator interaction for fault recovery. In general, the failure to sense and/or execute the mission-critical event(s) will cause mission failure or loss of a major mission objective.

Level 4. Includes Level 3 but is also capable of executing prespecified and stored command sequences based on timing and/or sensing of mission events. Ground-initiated changes to command sequences may be checked on-board for syntactical errors (parity, sign, logic, time). Uses coding or other self-checking techniques to minimize the effects of internally generated data contamination for prespecified data transfers. Requires ground-operator interaction for fault recovery. In general, failure to sense and/or execute the mission event(s) or state-changes (excluding failure-induced state-changes) will cause mission failure or loss of a major mission objective.

Level 5. Includes Level 4 and is also autonomously fault-tolerant. Is capable of operating in the presence of faults specified a-priori by employing spare system resources, if available, or will maximize mission performance based upon available capability and/or available expendables (i.e., self-loading of contingency programs) without ground intervention.

Level 6. Includes Level 5 and is capable of functional commanding with on-board command-sequence generation and validation prior to execution. Functional commanding may include a high-level, pseudo-English language, spacecraft-system/operator communication and control capability.

Level 7. Includes Level 6 and is capable of autonomously responding to a changing external environment, defined a-priori, so as to preserve mission capability. The capability to change orbit in order to compensate for degradation or to protect the satellite from an external threat is included.

Level 8. Includes Level 7 and is capable of operating successfully within the presence of latent design errors which could cause loss of major mission objectives.

Level 9. Includes Level 8 and is capable of task deduction and internal reorganization based upon anticipated changes in the external environment. This situation is exemplified by multiple satellites operating in a cooperative mode. In the event of a satellite failure, remaining satellites would detect autonomously the condition (task deduction) and may generate and execute orbit-and spacecraft-reconfiguration commands.

Level 10. Includes Level 9 and is capable of internal reorganization and dynamic task deduction based on unspecified and unknown/unanticipated changes in external environment. The system will strive to maximize system utility. Thus, mission objectives should be adaptive and automatically reprogrammable. System resources should be maximized to preserve task adaptiveness.

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